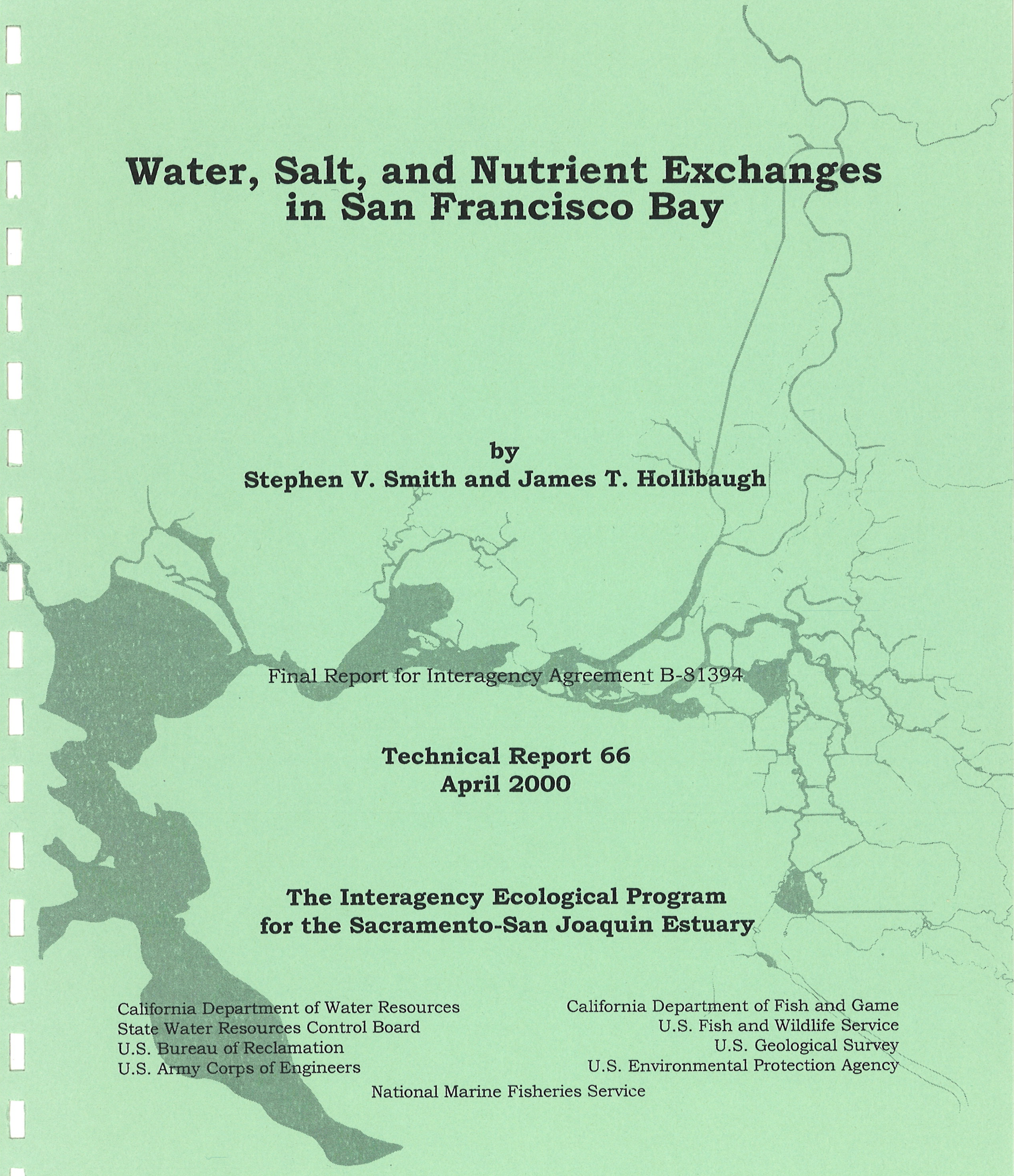

Water, Salt, and Nutrient Exchanges in San Francisco Bay

by

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Abstract

We constructed water, salt, and nutrient budgets for San Francisco Bay and used them to analyze the net biogeochemical performance of the bay. The bay was subdivided into three sectors, North Bay, Central Bay, and South Bay, with the Central Bay serving as a proxy for the "oceanic end-member." Separate budgets were constructed for the wet (October to March) and dry (April to October) seasons of each year for six years (1990–1995). This period of record contained two years of above normal runoff (1993 and 1995) and four years of below average runoff.

Sewage accounts for approximately 50% of the nutrient loading to the bay in winter and 80% of the summer loading. We conclude that overall the bay is slightly net autotrophic (production of new organic matter in the bay by plant growth exceeds respiratory demands); however, this varies seasonally (strongest in summer) and is complicated by abiotic P absorption in the North Bay. Both arms of the bay were apparently net heterotrophic during the winter, with this signal being strongest during the wet winters of 1993 and 1995.

We found the San Francisco Bay nutrient data set to be surprisingly sparse for the sort of biogeochemical mass balance analyses we performed. It would be highly desirable for future mass balance analyses and other geochemical modeling efforts to have better horizontal, vertical, and temporal resolution of bay water properties. The data that are available are minimal for defining the nutrient and salinity composition in the North Bay and for resolving weak horizontal gradients in the South Bay. Somewhat more detailed data on composition of freshwater reaching the bay (sewage, river, and possibly other sources) would be desirable, but better knowledge of the distribution in the bay is the critical weak point in the data.

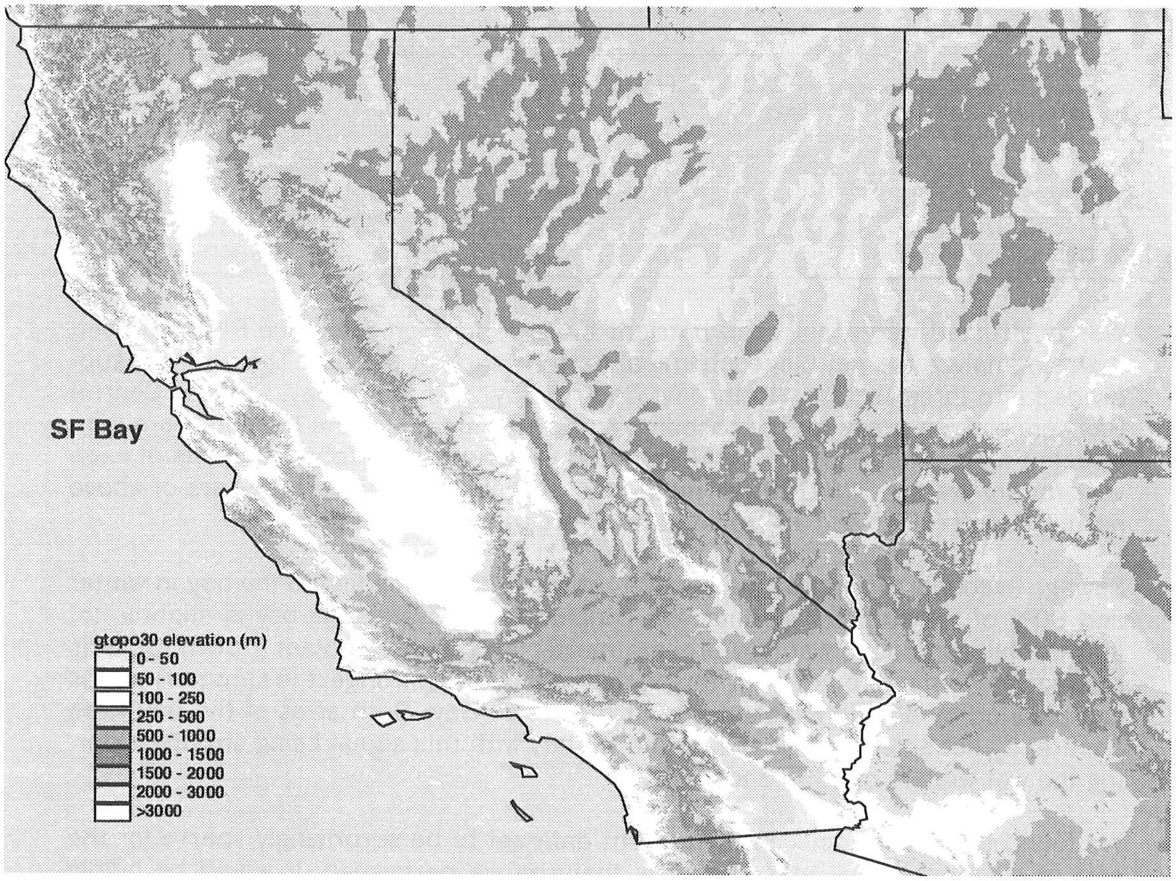

Figure 1 Water catchment regions for San Francisco Bay. Map based on gtopo30 GIS coverage, http://edcwww.cr.usgs.gov/landdaac/gtopo30. Note that the elevation intervals are not even; they have been chosen to accent the large, low elevation area of the catchments as well as the catchment boundaries.

Introduction

San Francisco Bay is one of the largest embayments on the Pacific coast of the Americas. With a human population of approximately seven million living around its perimeter, San Francisco Bay (Figures 1 and 2) has been referred to as the "urbanized estuary" (Conomos 1979). Human activity around the bay, as well as agricultural activity in California's Central Valley, have affected bay water quality and resulted in profound modifications of land and freshwater use. Water flow to the bay is modified by regulation for flood control and by diversions for consumptive use (Arthur and others 1996). While freshwater flow to the bay generally reflects interannual variations in precipitation within the watershed, the details of the annual hydrograph strongly reflect human control.

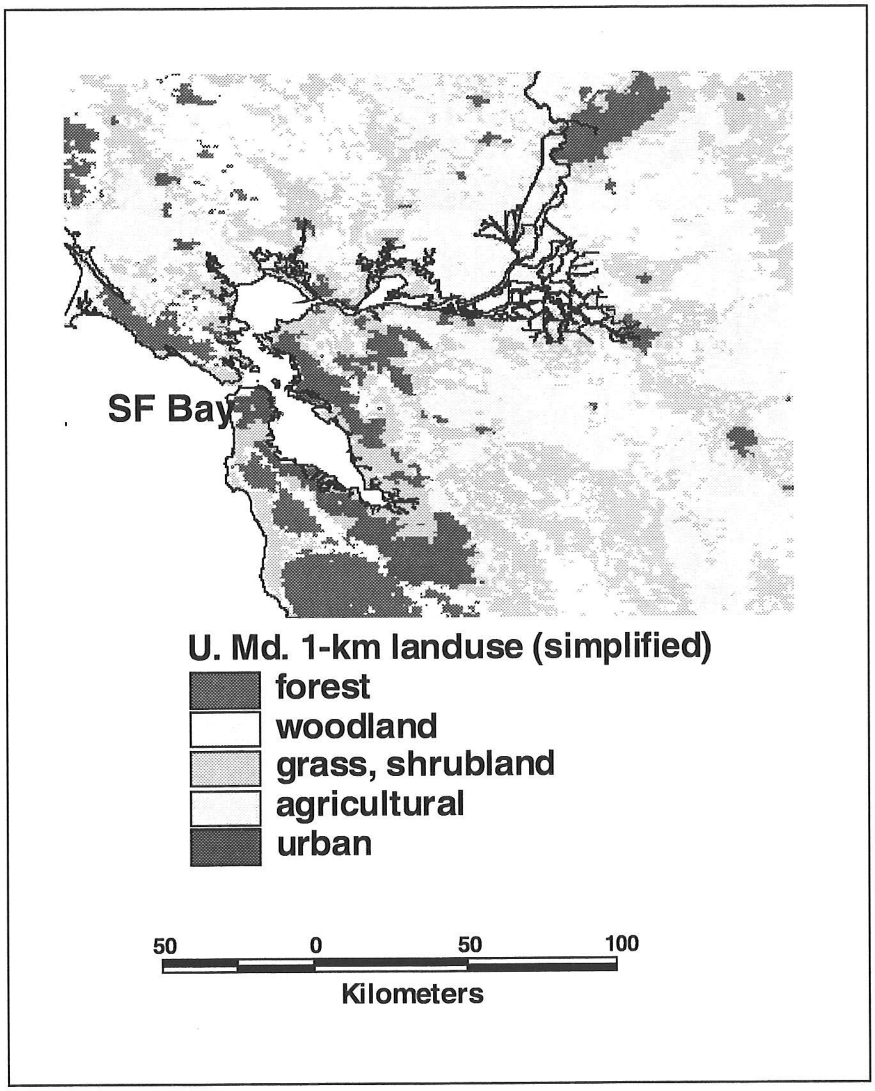

Figure 2 Land use in the San Francisco Bay region.
Modified from http://www.inform.umd.edu/Geography/landcover/1km-map.html.

The bay may be thought of as three hydrographically distinct basins (Conomos and others 1985): North Bay, Central Bay, and South Bay (Figure 3). North San Francisco Bay is a classical river-dominated, macrotidal estuary, receiving flow from the Sacramento and San Joaquin rivers and from several smaller rivers. These rivers drain an area of approximately 150,000 km^2, about 40% of the area of California. Much of the region is arid, but there is substantial precipitation in the Sierra Nevada mountain range. South San Francisco Bay and the Central Bay have very small catchment basins. The South Bay is a macrotidal marine embayment receiving little natural freshwater discharge. Sewage is the dominant freshwater input (Conomos 1985; Hager and Schemel 1996) and the South Bay can become slightly hypersaline (relative to the Central Bay) during the summer. These hydrologically distinct arms each exchange water with Central San Francisco Bay, which in turn exchanges water with the coastal Pacific Ocean via the Golden Gate (Walters and others 1985; Largier 1996).

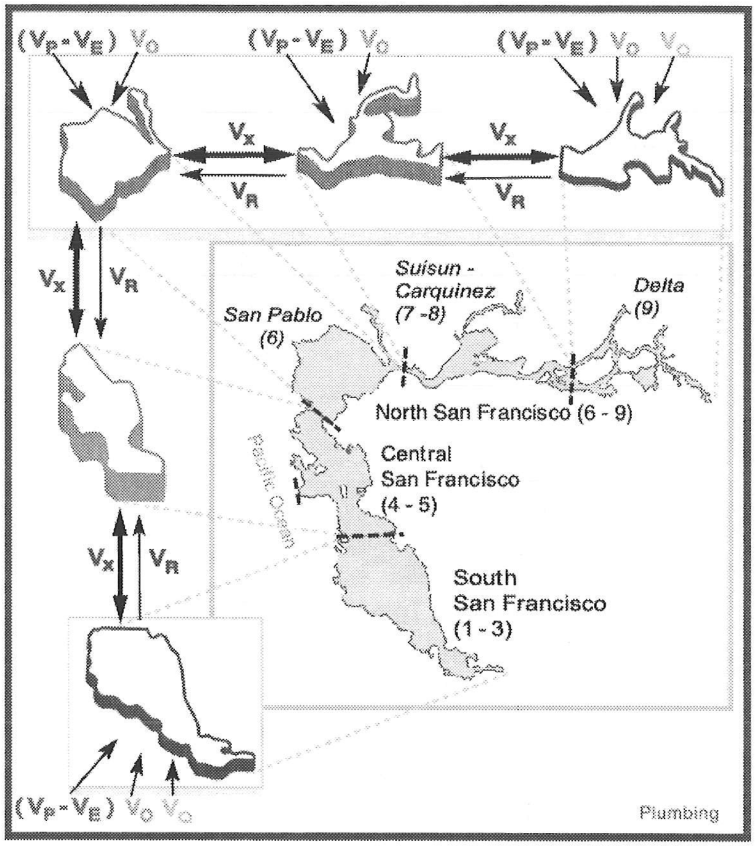

Figure 3 Idealized "plumbing diagram" used in developing the water, salt, and nutrient budgets for San Francisco Bay. The sector numbers shown on the boxes are also summarized in Table 1. The final analysis treated sectors 1–3 (South San Francisco Bay) as one box and sectors 6–9 (North San Francisco Bay) as a second box. Sectors 4–5 (Central San Francisco Bay) serve as the "oceanic end-member."

North and South San Francisco bays, although hydrologically distinct, are both strongly influenced by human perturbation. The San Francisco metropolitan area (approximately six million people) surrounds the bay (see Figure 2) and influences it in many ways. Moreover, agricultural activities and water diversion from North San Francisco Bay represent a further human perturbation associated with land and water use in the catchment. This report is concerned with water and nutrient dynamics of the San Francisco Bay ecosystem, so we will focus our attention on aspects of environmental modification most directly related to these aspects of the system.

A major perturbation to the bay at present appears to be regulation of river water flow. Historically the North Bay has also been modified extensively by large amounts of sediment and mercury discharge associated with gold mining in the mid-19th century. Water quality of North San Francisco Bay is strongly influenced by river discharge, although we will demonstrate possible additional influences within the North Bay itself. By contrast, sewage inflow dramatically alters water quality of the South Bay.

Conceptual Design

The purpose of the present study is to assess water and nutrient inputs to the bay and exchanges of these materials between North and South San Francisco Bay and the Central Bay. Specifically, we establish water budgets to estimate the flow of water through the system. Salt budgets provide estimates of mixing. These budgets can be considered "conservative"; that is, water and salt do not accumulate in the system, so over time water and salt inputs must equal outputs. Dissolved nutrients (nitrogen and phosphorus) are added along with the water and salt. Because of limited availability of data on organic nutrients, only inorganic nutrients are considered in our analysis. Unlike water and salt, the nutrients may either accumulate within the system or be consumed there. Budgets of these materials are termed "non-conservative" with respect to both water and salt, because processes other than water flow and mixing take up and release dissolved inorganic N and P. These processes include the biotic reactions of primary production, respiration, nitrogen fixation, and denitrification, and abiotic reactions such as sorption or desorption from sediment and co-precipitation. For examples of the application of these techniques to nearby Tomales Bay, see Smith and Hollibaugh (1997) and references found at http://www.soest.hawaii.edu/Tomales_Bay/.

The budgetary procedure we use has been formalized into the standard protocol for an international research program called "Land Ocean Interactions in the Coastal Zone" (LOICZ). The guidelines for the procedure are in Gordon and others (1996), and an extended version of the procedure, along with many individual biogeochemical budgets, can be found at http://www.nioz.nl. One of us (SVS) oversees the biogeochemical budgeting exercise for LOICZ.

Figure 3 presents an index map of San Francisco Bay, together with the "plumbing diagram" that was used to assess water, salt, and nutrient budgets in San Francisco Bay. The two arms of the bay are treated independently in the analysis. The budget was initially developed with North San Francisco Bay treated as three sectors in series (Delta, Suisun Bay-Carquinez Straits, and San Pablo Bay). Because water exchange time in the Delta and Suisun Bay-Carquinez Straits sectors is short, their budgets proved to be unreliable. Nevertheless, as discussed by Webster and others (1999), the overall analysis of a system this complex is more accurate if the system is segmented. The segmentation provides a "box-model approximation" of the longitudinal gradients in water properties, and estimates of salt exchange according to equations presented below are more accurate than they would be with larger boxes. Consequently, we have performed the analyses for the three sectors and then combined the data into estimates for the entire North Bay. The Central Bay is treated as the "oceanic end-member" for both North and South bays. While it would be desirable to budget the Central Bay as well as the North and South bays, the analytical protocol employed here requires water composition data on the oceanic side of each budgeted box. Because the coastal ocean outside the Golden Gate is hydrographically complex (Largier 1996) and is not sampled routinely, it was only feasible to use the Central Bay as the oceanic end-member for this analysis.

Seasonal and interannual variability in rainfall and runoff are high, and both water exchange and delivery of nutrients and other materials are influenced by this variability. Water composition is strongly responsive, with clear seasonal and interannual differences (for example, Peterson and others 1985; Hager and Schemel 1996; Schemel and Hager 1996). To capture these time scales of variability in our analysis of the system, we used hydrological and climatological data for water years (October 1 to September 30) 1989–1990 to 1995–1996. (Hereafter the water year will be referred to by the second calendar year, in other words, water year 1989–1990 is referred to as "1990"). We constructed budgets for summer (April to October: dry season) and winter (October to April: wet season). This period includes four years with below normal runoff (dry: 1990–1992, and 1994) and two years with above normal runoff (wet: 1993 and 1995). The water quality data for Central San Francisco Bay needed to establish the oceanic end-member were not available for summer 1990, so that period is missing from our analysis.

North San Francisco Bay stratifies periodically, particularly in response to gravitational circulation during periods of neap tides and high flows (Monismith and others 1996). While this stratification is pulsed (in other words, ephemeral), the budgetary analysis might be considerably strengthened if the data were available to calculate the effects of stratification on the budgets (Webster and others 1999). Unfortunately, the development of a two-layer budget model for this system is not feasible due to data limitations. Because the stratification is ephemeral, we assume that this is not a major limitation of the analysis. The budgets developed here are therefore based on linked one-dimensional sectors, or boxes, along the bay.

Consider any coastal box adjacent to land. We can write the following equation for conservation of water within the volume of the system V_{syst}:

$$\frac{dV_{syst}}{dt} = V_Q + V_P + V_E + V_G + V_O + V_R \qquad (1)$$

Note that V_{syst} has the units of volume; this volume is divided by time, giving the units of volume/time; the Vs on the right side of the equation are directly in units of volume/time. As expressed here, V_Q, V_p, V_E, V_G, and V_O represent river flow, precipitation, evaporation, groundwater, and any other flows into the system, respectively. V_G can be assumed to be minor relative to the other freshwater sources in San Francisco Bay and the major flow associated with V_O in this system is likely to be sewage. By convention, flow into the system is positive, so V_E (which represents removal of water) has a negative value. We also assume that the volume of the system remains constant, so the left side of the equation is 0. Of course volume fluctuates with tidal oscillation, meteorological forcing, and so on, so this latter assumption is not strictly true over relatively short time periods (biweekly or less). Over long time scales (years to decades or more) sedimentation, dredging, diking, etc. can affect V_{syst}. Over the periods of months to years considered in this analysis, there is no significant net change in bay water volume. This steady-state assumption may be thought of as describing either the tidally-averaged water volume or water volume of the system at a constant tidal state (for example, mean sea level).

This leaves one undefined term in the equation: V_R. This term (called "residual flow") represents the amount of water flow that must occur to balance the budget. In river-dominated North San Francisco Bay, V_R is always negative because of the "excess water" delivered by the river. That is, residual outflow is required to balance the water budget. Neglecting the smaller terms in the equation, $V_R = -V_Q$ (residual flow is approximately equal to the negative of river flow) in the North Bay. By contrast, the other terms become important in South San Francisco Bay. During the summer (dry season), V_E can exceed the other terms. V_R then becomes positive (in other words, residual flow into the South Bay) to compensate for evaporative water loss. If dV_{syst}/dt is assumed to be 0, Equation (1) can be solved with V_R as the unknown, retaining all of the other terms:

$$V_R = V_Q - V_P - V_E - V_G - V_O \tag{2}$$

An analogous equation can be written to describe the salt balance by multiplying water fluxes by their appropriate salinity (equation 3). Subscripts on the various salinity (S) terms represent the salinity of each water flux. The equation is usually simplified by omitting terms likely to be insignificant in the salt budget. River water, precipitation, evaporation, groundwater (usually), and "other" can all be assumed to have negligible salinity. The salinity of the residual flow is assumed to be that at the boundary between the box of interest (the system) and the adjacent source box (usually the oceanic end-member). This salinity is estimated as the average of those two boxes, in other words, $S_R = [S_{syst} + S_{ocn}]/2$. The salt budget has one term that does not appear in the water budget, because mixing occurs between the system and the ocean. The mixing term (V_X) can be visualized as adding and removing an equivalent amount of water. There is no net flux of water, hence no need for the term in equation (1); but the inflowing and outflowing water contain different amounts of salt. This derivation of mixing is not dynamic, as in a numerical or analytical circulation model; rather, it is the mass balance consequence of those circulation processes that act to exchange water between sectors of the bay. With the above simplifications and explanation, the salt budget is represented by the following equation:

$$\frac{d(V_{syst}S_{syst})}{dt} = V_R S_R + V_X(S_{ocn} - S_{syst}) \tag{3}$$

Note that the term $(S_{ocn} - S_{syst})$ is the box model equivalent of the horizontal salinity gradient. We again make the steady state assumption that the left side of the equation is 0. This assumption need not be made if the temporal change in salinity is determined explicitly (Smith and others 1991), but in relatively shallow-water systems the change in salt mass with time is usually demonstrably small. We can then solve for V_X:

$$V_X = \frac{V_R S_R}{(S_{ocn} - S_{syst})} \tag{4}$$

As long as there is a measurable salinity difference between the system of interest and the adjacent "oceanic water," equations (2) and (4) become a simple but powerful pair of equations for describing the water exchange between many water bodies and the adjacent ocean. Various more complex versions of the equations can be offered (multiple boxes, stratification, non-steady state composition, and so on) if system complexity warrants the complication and data are available for the analysis (see Gordon and others 1996, as well as the previously cited LOICZ modeling page web address). It is important to note that in some systems there is no significant horizontal salinity gradient; under these circumstances the equations do not work because the denominator of equation (4) becomes 0 and the equation blows up (V_X becomes infinite). Moreover, if V_X is derived to be a negative number, then there is a problem with the analysis; a negative value for V_X is a physical impossibility.

Water exchange time (τ; sometimes called residence time, although this term has been used for a variety of differing calculations) can be derived as the system volume divided by the sum of V_X and the absolute value for V_R:

$$\tau = \frac{V_{syst}}{(V_X + |V_R|)} \tag{5}$$

This equation represents the combined effects of water advection and water mixing on the time to replace the water in the system. Both V_X and V_R may be thought of as water that is replacing the system volume.

We are aware of one potential complication in applying this model to San Pablo and South San Francisco bays: the harvest and removal of salt by seawater evaporation to dryness. That is, salinity is not strictly conservative relative to water in this system. At the scale of the bay, however, this term is small and is not included in the analysis.

Once equations (2) and (4) have been used to provide a simple definition of water exchange (including both advection and mixing), an equation analogous to (3) is written to describe any material (Y). We limit the analysis to dissolved materials because particulate material budgets are complicated by sedimentation and resuspension that are not readily accounted for in budgets based on water and salt balances. We include the terms for river flow and other sources in the equation, because clearly river flow and sewage contribute nutrients to the system even though they are negligible for salt or (for sewage) water budgets. If we had groundwater data, we would add this information as well. The inclusion of groundwater in the nutrient budget may (in principle) seem at odds with omitting it from the water and salt budgets, but that is not the case. Nutrients concentrations can be high in groundwater, so it may contribute significantly to the nutrient budget. We were unable to constrain this term in our analysis due to lack of data, so it has been omitted from the budget.

ΔY is the sum of all processes affecting the system other than the hydrographic processes. Thus,

$$\frac{d(V_{syst}Y_{syst})}{dt} = V_Q Y_Q + V_O Y_O + V_R Y_R + V_X(Y_{ocn} - Y_{syst}) + \Delta Y \qquad (6)$$

An estuary like San Francisco Bay might well receive significant atmospheric deposition, especially of nitrogen. This input could be treated as a known term (N_{atm}) or included as part of ΔY if it is not explicitly known. We again make the steady state assumption and rearrange the equation to solve for ΔY as the unknown.

$$\Delta Y = -V_Q Y_Q - V_O Y_O - V_R Y_R - V_X(Y_{ocn} - Y_{syst}) \qquad (7)$$

Equations (2), (4), (5), and (7) constitute the essence of our analysis of the San Francisco Bay data. V_R, V_X, and τ have been calculated for water, and ΔYs have been determined for dissolved inorganic P and dissolved inorganic N (ΔDIP and ΔDIN) in the two reaches of San Francisco Bay, for 11 different periods (five summer and six winter). ΔDIP and ΔDIN are normalized to the areas of each arm of the bay so that rates are expressed per unit area of the budgeted regions for ease of comparison between the two arms and with the literature. We have made two additional stoichiometric calculations.

The first calculation provides an estimate of net ecosystem metabolism. The assumption made in the LOICZ analysis (Gordon and others 1996) is that the major non-conservative reaction involving DIP is the production or consumption of organic matter, and that any organic matter being produced or consumed has a carbon-to-phosphorus ratio approximating that of phytoplankton (the so-called "Redfield C:P ratio," in molar units, 106:1). Net organic production removes DIP, while net organic consumption (respiration or oxidation of organic matter by bacteria or secondary producers) releases DIP. Net production minus respiration can be denoted as $(p-r)$, so:

$$(p - r) = -106 \times \Delta DIP \qquad (8)$$

A system that is net autotrophic [(*p–r*) > 1] produces organic matter in excess of respiration and requires an input of inorganic nutrients supplied from outside the system to support this positive net ecosystem production. A system that is net heterotrophic requires a source of organic matter supplied from outside the system to support this net heterotrophy (Smith and Hollibaugh 1997). The assumption that ΔDIP is only the result of organic metabolism may be considered a first approximation. It will eventually be demonstrated that this assumption is not entirely valid for San Francisco Bay.

The second stoichiometric calculation involves both nitrogen and phosphorus. Many coastal ecosystems denitrify at relatively rapid rates; a few fix atmospheric nitrogen into organic material (Gordon and others 1996; Smith and Hollibaugh 1997). Again, ΔDIP is used as a tracer of net organic metabolism. The Redfield N:P ratio (16:1) would predict that for each mole of DIP either released or taken up by organic metabolism, there should be 16 moles of ΔDIN released or taken up. We refer to this as ΔDIN_{exp}, the "expected change in DIN." This value may differ from the observed change in DIN, ΔDIN_{obs}. The difference between observed and expected ΔDIN is attributed to the difference between nitrogen fixation and denitrification (*nfix–denit*):

$$(nfix - denit) = \Delta DIN_{obs} - \Delta DIN_{\exp} = \Delta DIN_{obs} - 16 \times \Delta DIP \qquad (9)$$

Equations (8) and (9) are thus used to place initial biogeochemical interpretations on ΔDIP and ΔDIN in San Francisco Bay. Again, it will be demonstrated that the stoichiometric assumption cannot be entirely correct in this system.

Materials and Methods

We have used data from technical reports and unpublished records to perform the analyses presented here. Many of these data are available via the internet. URLs are given where appropriate and data report citations are given in the references.

North Bay river flow data (Q_{out}) are from the Dayflow web page (http://www.cd-eso.water.ca.gov/ndfriend/dayflow/), as calculated by the California Department of Water Resources (DWR). South Bay runoff is approximated from gauged streams (http://waterdata.usgs.gov/nwis-w/CA/). Runoff coefficients (in other words, measured flow/gauged catchment area) times total catchment areas were used to estimate runoff for the whole South Bay watershed. Bay and river water quality data were provided, as discussed below, by the US Geological Survey (USGS) and DWR. Most of the salinity estimates available for the North Bay were based on DWR measurements of chlorinity. A standard oceanographic assumption is that salinity ≈ 1.806 x chlorinity. Although this conversion factor is most valid at salinities near those of open ocean seawater (in other words, salinity ≈ 35), this factor is sufficiently accurate for use in the North Bay budget because the chlorinity gradients are relatively large. In some cases, data on specific conductance were converted to salinity estimates.

Sewage discharge data were obtained for 12 major municipal sewage treatment plants (STPs) discharging to the bay. These data were provided either by the San Francisco Bay Regional Water Quality Control Board or, in two cases, from STP records. Five of the plants (accounting for about half of the sewage load into San Francisco Bay) recorded effluent composition with enough detail on dissolved inorganic nitrogen and phosphorus concentrations to be used in the budgets. We assume that these data are representative of effluent composition for other treatment plants for which data were not available.

Combined sewage discharge rate was assumed to be constant over the six years budgeted here, an assumption that is supported by inspection of the data. Water discharged by the STPs is not significant to the water budget. Storm drains have been separated from sewage lines in the majority of these systems, removing a major source of intrannual variation in flow. Storm runoff is budgeted separately in our analysis. Seasonal and interannual variation in nutrient discharge from these plants over the period of record was judged to be unimportant for the analysis of loadings presented here. Additional information on local inflows of materials from a San Francisco Bay Conservation and Development Commission report (Anonymous 1992) were examined, although these data were not used explicitly in the analysis.

Runoff composition data for the South Bay are poorly characterized. The reason, of course, is that there are several small sources, rather than the dominating influence of a single large river system, as is the case for North San Francisco Bay. We were unable to locate a data repository for South Bay runoff composition, although there are undoubtedly individual databases, so we assumed composition to be similar to the Sacramento-San Joaquin river composition. While this estimate is crude, it is sufficient to demonstrate that nutrient discharge to the South Bay is overwhelmingly dominated by sewage, a conclusion supported by previous work (Conomos and others 1979; Hager and Schemel 1996; Schemel and Hager 1996).

Weather data used to calculate runoff and net evaporation were downloaded from the National Oceanographic and Atmospheric Administration (NOAA) website (http://www.ncdc.noaa.gov/ol/climate/stationlocator.html). We used five stations located around South San Francisco Bay because of the obvious dominance of river flow (which is measured directly) in the freshwater budget of North Bay. Monthly mean rainfall data were used to calculate runoff and net evaporation. Evaporation data for the period were smoothed with an annual sine curve, that is, the seasonal pattern is treated as being the same between years. This approximation is justified because net evaporation is significant only during the summer, and there is less interannual variation in summer climatology than in winter runoff. San Francisco Bay nutrient data were collected in conjunction with the USGS's San Francisco Bay Program and were provided by S.W. Hager (USGS). Other San

Francisco Bay water quality data used in our analysis (temperature, salinity) were also collected by that program and are posted at http://www.sfbay.wr.usgs.gov/access/wqdata/query. These data are also contained in the following technical reports: Wienke and others (1990, 1991, 1992, 1993); Caffrey and others (1994); Edmunds and others (1995, 1997). We obtained additional data for North San Francisco Bay and the Sacramento and San Joaquin rivers from DWR. Hypsographic data were approximated by planimetry of hydrographic charts of San Francisco Bay.

Results

General

Table 1 and Figure 4 summarize hypsographic information for various sectors of San Francisco Bay. Central San Francisco Bay, which is not budgeted, is the deepest portion of the bay (10 m) and accounts for about 36% (430 km^2) of the bay area. North San Francisco Bay is next in depth (5 m) and accounts for 42% (490 km^2) of the area. South San Francisco Bay is about 4 m deep and covers about 260 km^2 (22%) of the area. The overall area of the San Francisco Bay (about 1,200 km^2) makes it the largest estuary on the Pacific coast of the US and one of the largest estuaries in the country.

Table 1 Hypsographic characteristics of San Francisco Bay [a]

Region	*Sector*	*Area (10^6 m^2)*	*Average Depth (m)*	*Volume (10^6 m^3)*
South San Francisco Bay				
South of Dumbarton Bridge	1	30	3	90
Dumbarton Bridge to San Mateo Bridge	2	90	4	360
San Mateo Bridge to San Bruno Shoal	3	140	4	560
Subtotal	1-3	260	3.9	1,010
Central San Francisco Bay				
San Bruno Shoal to Bay Bridge	4	230	7	1,610
Bay Bridge to San Pablo Point	5	200	12	2,620
Subtotal	4-5	430	9.8	4,230
North San Francisco Bay				
San Pablo Bay	6	290	5	1,450
Carquinez Strait	7	20	12	240
Suisun Bay	8	100	5	500
Delta	9	80	2	160
Subtotal	6-9	490	4.8	2,350
Total San Francisco Bay	1-9	1,180	6.4	7,590

[a] The sectors originally budgeted are labeled. The final budgets are based on combining sectors 1-3 into one budget box, sectors 6-9 into a second budget box, and using combined sectors 4 and 5 as the oceanic end-member.

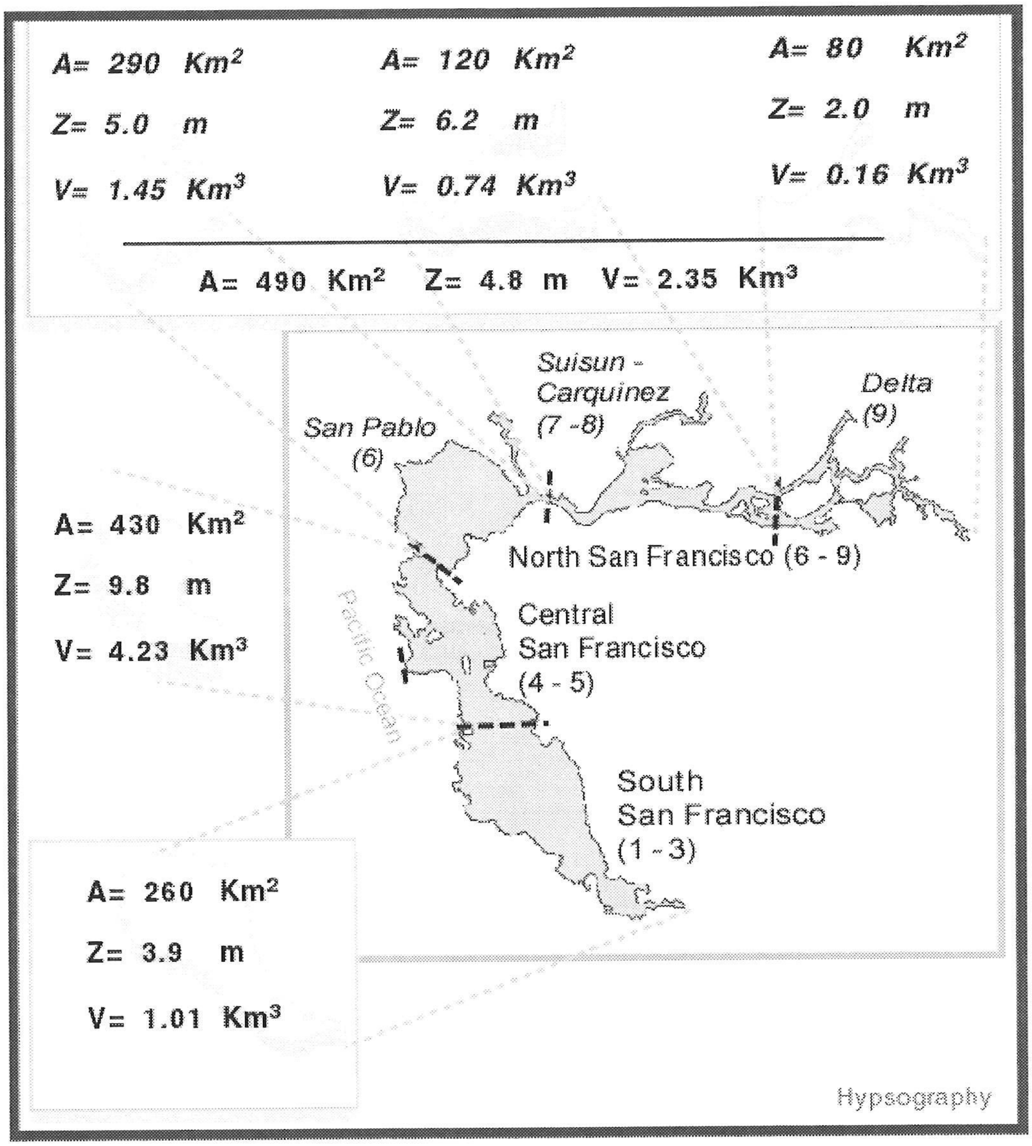

Figure 4 Hypsography (area, volume, depth) of San Francisco Bay sectors

Figure 5 presents monthly water inputs to North and South San Francisco Bay, and shows the net (or residual) flow necessary to balance the inflow. The important points to note are as follows. Freshwater input is dramatically different between the two portions of the bay, with the South Bay being dominated by sewage input and the North Bay being overwhelmingly dominated by runoff. There is strong seasonality, with the winter months having high freshwater inflow and the summer having low freshwater inflow. In the South Bay this is manifested by net water loss via evaporation during the summer. Finally, note the high interannual variability. The years 1990, 1991, 1992, and 1994 are grouped together as dry years; the years 1993 and 1995 are wet years. Comparisons proceed on the basis of this separation.

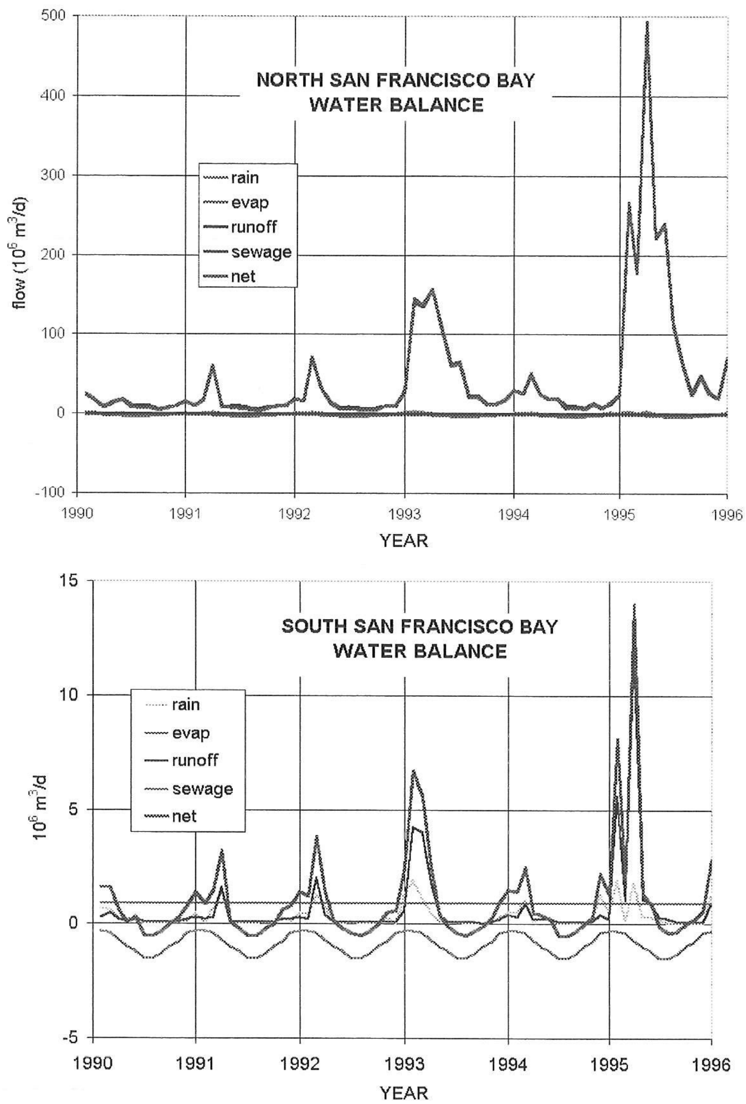

Figure 5 Freshwater balance for North and South San Francisco Bay. The North Bay freshwater budget is overwhelmingly dominated by river inflow. By contrast, the South Bay budget includes significant amounts of water from rainfall, evaporation, runoff, and especially sewage.

Water and Salt Budgets

Tables 2 and 3 summarize data from 1990 through 1995 that were used in the water and salt budgets. Higher precision is maintained on the water flux estimates for the South Bay than for the North Bay because of the small (and similar) magnitudes of each of the freshwater fluxes in the South Bay. During most years, the strong seasonality of rainfall and runoff (wet winters, dry summers) is reflected in the water budgets. There is considerable interannual variability—1993 and 1995 are decidedly wetter than the other years represented in the budgets. There are also large differences between the water budgets for the two reaches of the bay.

Table 2 Freshwater fluxes (10^6 m^3/d) into the sectors of San Francisco Bay [a]

				North San Francisco Bay								
	South San Francisco Bay			*San Pablo Bay*			*Suisun Bay - Carquinez Straits*			*Delta*		
Period [b]	(V_P-V_E)	V_O	V_Q	(V_P-V_E)	V_O	V_Q	(V_P-V_E)	V_O	V_Q	(V_P-V_E)	V_O	V_Q
w-90	-0.4	0.9	0.3	0.0	0.1	0	-0.2	0.2	0	0.0	0.0	14
w-91	0.0	0.9	0.7	0.0	0.1	0	0.0	0.2	0	0.0	0.0	29
w-92	0.0	0.9	0.8	0.0	0.1	0	0.0	0.2	0	0.0	0.0	39
w-93	-0.1	0.9	2.1	0.0	0.1	0	-0.1	0.2	0	0.0	0.0	133
w-94	-0.2	0.9	0.4	0.0	0.1	0	-0.1	0.2	0	0.0	0.0	32
w-95	0.0	0.9	4.7	0.0	0.1	0	0.0	0.2	0	0.0	0.0	297
s-90	-1.0	0.9	0.1	-2.0	0.1	0	-0.5	0.2	0	0.0	0.0	8
s-91	-0.9	0.9	0.1	-2.0	0.1	0	-0.5	0.2	0	0.0	0.0	8
s-92	-0.9	0.9	0.1	-2.0	0.1	0	-0.5	0.2	0	0.0	0.0	9
s-93	-1.0	0.9	0.1	-2.0	0.1	0	-0.5	0.2	0	0.0	0.0	16
s-94	-1.0	0.9	0.1	-2.0	0.1	0	-0.5	0.2	0	0.0	0.0	10
s-95	-1.0	0.9	0.1	-2.0	0.1	0	-0.5	0.2	0	0.0	0.0	34

[a] "V_O" is estimated (constant) sewage influx. "V_Q" (runoff) into the North Bay sectors from sources other than the Delta is small and is assumed to be 0.
[b] w = winter, s = summer. Shaded winter periods (1993, 1995) are wet years.

Table 3 Estimated salinity (PSU) in San Francisco Bay sectors during each sampling period [a]

Period [b]	*South Bay*	*Central Bay*	*San Pablo Bay*	*Suisun Bay - Carquinez Straits*	*Delta*
w-90	28.6	29.6	27.6	9.3	7.5
w-91	27.1	28.2	23.7	6.6	4.7
w-92	25.1	27.6	23.1	2.7	1.5
w-93	17.9	20.3	17.3	0.2	0.2
w-94	26.0	27.0	24.7	4.3	2.9
w-95	13.6	14.3	5.6	0.1	0.1
s-90			29.2	9.6	7.6
s-91	31.8	31.9	29.7	10.0	7.7
s-92	30.5	31.9	29.4	10.7	8.6
s-93	27.6	28.8	23.4	4.7	3.2
s-94	31.4	31.7	29.5	10.6	8.3
s-95	25.1	27.7	19.0	2.4	0.6

[a] Central San Francisco Bay is used as the oceanic end-member. The highlighted winter periods (1993 and 1995) are wet years. Runoff, sewage, and (rainfall - evaporation) are assigned salinities of 0.
[b] w = winter, s = summer. Shaded winter periods (1993, 1995) are wet years.

Of the water budget terms illustrated in Figure 5, no single term can be ignored for South San Francisco Bay. During the summer, evaporation dominates. The South Bay can become slightly more saline than the Central Bay because evaporation is only partially offset by sewage inflow, which is the largest summer freshwater input. Runoff dominates the budget during the winter, but rainfall is significant. The pattern is very different in North San Francisco Bay because the budget is overwhelmingly dominated by runoff.

Table 4 presents the year-by-year water and salt budgets for the two reaches of the bay. Water quality data were relatively sparse, and the lack of data to develop vertically stratified budgets is a particular shortcoming of the analyses presented here. Because the data are sparse, it was impractical to use direct statistical estimates of variability to evaluate sensitivity. Nevertheless, some measure of the uncertainty of the various budget-derived estimates is desired. We have therefore used a simple Monte Carlo analysis (for example, Laws 1997) with 100 re-samplings to estimate mean, median, and standard deviations of V_R and V_X. It was assumed that the errors were normally distributed and that there was a 25% uncertainty (standard deviation) in the water budget terms and a 1 psu uncertainty in the mean salinity within each box. Note that in some instances the standard deviations became very large as the denominator of equation (4) approached 0. Negative values for V_X arise from random error when the signal of the salinity gradient (in other words, $S_{ocn} - S_{syst}$) becomes small and indistinguishable from 0 and is a physically impossible condition. Deviations between the direct budget calculation and the mean Monte Carlo value are largest when the standard deviation is large, reflecting the appearance of a few extreme calculations. This interpretation is supported by the general agreement between the budget value and the Monte Carlo median, which is less sensitive than the mean to extremes. Using more complex estimates of error distributions was deemed unwarranted by the limited amount of data available to test their applicability.

Because of the lack of data from the lower water column, we were unable to evaluate the uncertainties (or errors) in the budgets that resulted from using only surface data and a single-layer box model. Budget-derived estimates for which the median flux estimate (see Table 4) differed by more than 50% (in other words, outside the range of 0.5 to 1.5 times the budget flux estimates) were deemed unacceptable. The rule is changed for the very low V_R values in the South Bay during the summer; under those conditions the slight ($<0.5 \times 10^6$ m^3/d) differences are all regarded as acceptable. Out of 22 separate budgetary analyses, four estimates of V_X and none of the estimates of V_R (other than the very low summer South Bay values), fell outside the 50% criterion. Two unacceptable values occurred in the South Bay during the winter and two occurred in the South Bay during the summer. Despite the uncertainties, generalities emerge from the water and salt budgets and are discussed below.

Table 4 Estimated values for V_{Q*} (defined as the sum of the freshwater inputs $\equiv -V_R$, the residual flow) and V_X for North and South San Francisco Bay during the budgeted periods [a]

	$V_{Q*} = -V_R$				V_X			
Period [b]	budget	mean	s. d.	median	budget	mean	s. d.	median
North San Francisco Bay								
w-90	14	14	4	14	202	161	649	164
w-91	29	29	8	29	168	203	108	167
w-92	39	38	9	38	220	232	99	201
w-93	133	134	34	132	834	1,142	1,838	858
w-94	32	31	8	32	361	16	3,449	294
w-95	297	313	86	318	340	365	108	361
s-90	6	6	2	6	---	---	---	---
s-91	6	6	2	6	85	821	6,988	75
s-92	7	7	2	7	87	133	353	84
s-93	14	14	4	14	68	74	31	67
s-94	8	8	2	9	113	–36	1,223	108
s-95	32	31	7	30	86	87	26	84
South San Francisco Bay								
w-90	0.8	0.9	0.4	1.0	23	19	86	12
w-91	1.6	1.7	0.5	2.0	41	9	550	22
w-92	1.7	1.8	0.5	2.0	18	39	193	19
w-93	2.9	2.9	0.7	3.0	23	20	163	20
w-94	1.1	1.1	0.3	1.0	*29	23	141	13
w-95	5.6	5.7	1.4	6.0	*113	13,331	126,885	36
s-90	0.0	0.0	0.3	0.0	---	---	---	---
s-91	0.1	0.0	0.4	0.0	*30	7	33	0
s-92	0.1	0.1	0.5	0.0	*2	15	107	0
s-93	0.0	0.0	0.4	0.0	0	0	7	0
s-94	0.0	0.0	0.4	0.0	0	1	23	0
s-95	0.0	0.0	0.4	0.0	0	–1	11	0

[a] Fluxes in 10^6 m^3/day. Values shown are the budget estimates, and the mean, standard deviation, and median of 100 Monte Carlo analyses. Budgeted flux values marked with an asterisk (*) are not significantly different from 0 according to the uncertainty criterion given in the text.

[b] w = winter, s = summer. Shaded winter periods (1993, 1995) are wet years.

Table 5 and Figures 6 and 7 summarize the estimates of water exchange time (τ) as calculated from equation (5). As would be expected, water exchange time for both North and South Bay is shorter during the wet season (winter and spring) than the dry season (summer and fall). During the wet season, the North Bay exchange time is typically one to two weeks during dry years and less than one week during wet years. North Bay exchange during the dry season is about three weeks. South Bay wet season exchange time is typically about five weeks. The very wet year of 1995 had an exchange time near one week; however, it should be noted that the budgetary calculation of mixing (V_X) was extremely unstable during that period (see Table 4). Dry season water exchange in the South Bay is very slow, with all but one year having exchange times that were effectively infinite. That is, within the limitations of the salt and water budget calculations, water exchange in the South Bay during summer is effectively 0. There obviously is water exchange during this period (for example, by tides), but the resolution of salinity and freshwater fluxes is not adequately constrained to determine the exchange.

Nutrient Budgets

Nutrient concentrations are summarized in Table 6, and nutrient loadings are presented in Tables 7 and 8 and Figures 8 through 11. In the North Bay, the major input of both DIN and DIP is river inflow, while sewage input dominates in the South Bay. These conclusions would not be significantly affected by more detailed information on other sources because of the strong dominance of these sources. The river load to the North Bay is, of course, much higher in the winter than in the summer and fluctuates strongly with river flow. During the summer, river and sewage delivery of DIN and DIP to the North Bay are of similar magnitude. In contrast, DIN and DIP loadings to the South Bay are always sewage-dominated. Table 9 summarizes the nutrient budgets, including both the direct budgetary calculations and the Monte Carlo analysis as discussed above.

The Monte Carlo analysis includes uncertainty in the water and salt budget (same rules as given above) and uncertainty in the nutrients (50% uncertainty [standard deviation] in the mean concentrations within the system; 33% uncertainty in the sewage nutrient concentrations). Even with these large uncertainties, there is generally good agreement among the direct budgetary calculations and the means and medians from the Monte Carlo analysis. The one significant exception occurred during winter 1995 when there was a substantial discrepancy between the DIP budget and Monte Carlo calculations of mean fluxes in both the North Bay and South Bay. Because the problem did not carry over to the DIN budget or the salt and water budget, it suggests the uncertainty lies with the DIP data.

Table 5 Water exchange time, as calculated according to equation (5) from data in Tables 1 and 4 a

Period [b]	$-V_R$ 10^6 m^3/d	V_X 10^6 m^3/d	τ days
North San Francisco Bay (V_{syst} = 2,350 x 10^6 m^3)			
w-90	24	202	10
w-91	29	168	14
w-92	39	232	10
w-93	133	1,142	2
w-94	32	16	6
w-95	297	365	4
s-90	6	—	—
s-91	6	85	26
s-92	7	87	26
s-93	14	68	29
s-94	8	113	19
s-95	32	86	20
South San Francisco Bay (V_{syst} = 1,010 x 10^6 m^3)			
w-90	1	23	42
w-91	2	41	23
w-92	2	18	51
w-93	3	23	39
w-94	1	*29	34
w-95	6	*113	8
s-90	0	—	—
s-91	0	*30	34
s-92	0	*2	505
s-93	0	0	∞
s-94	0	0	∞
s-95	0	0	∞

[a] Calculations are based on the budget values of V_{Q^*} and V_X. Budgeted flux values marked with an asterisk (*) fail statistical significance criterion given in the text.

[b] w = winter, s = summer.

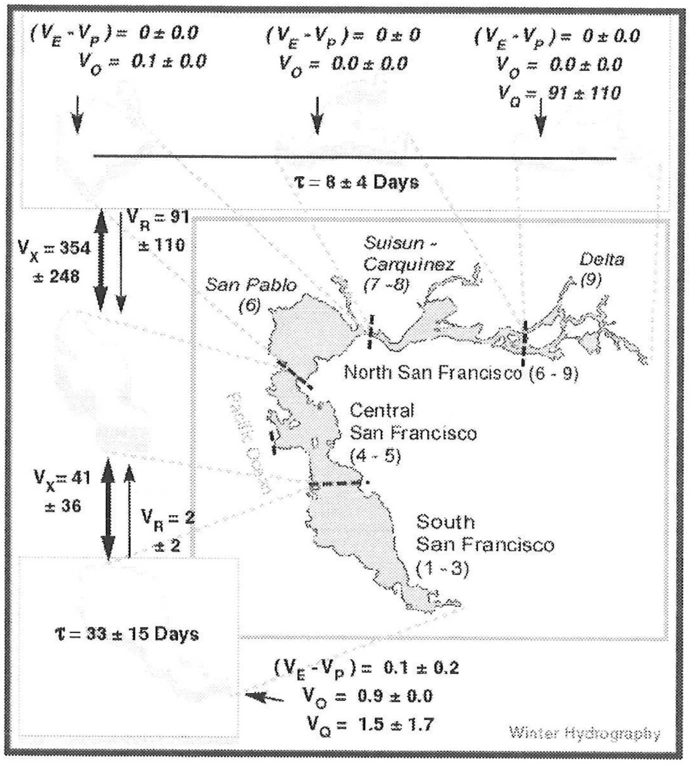

Figure 6 Winter hydrographic fluxes (10^6 m^3 d^{-1}) in San Francisco Bay

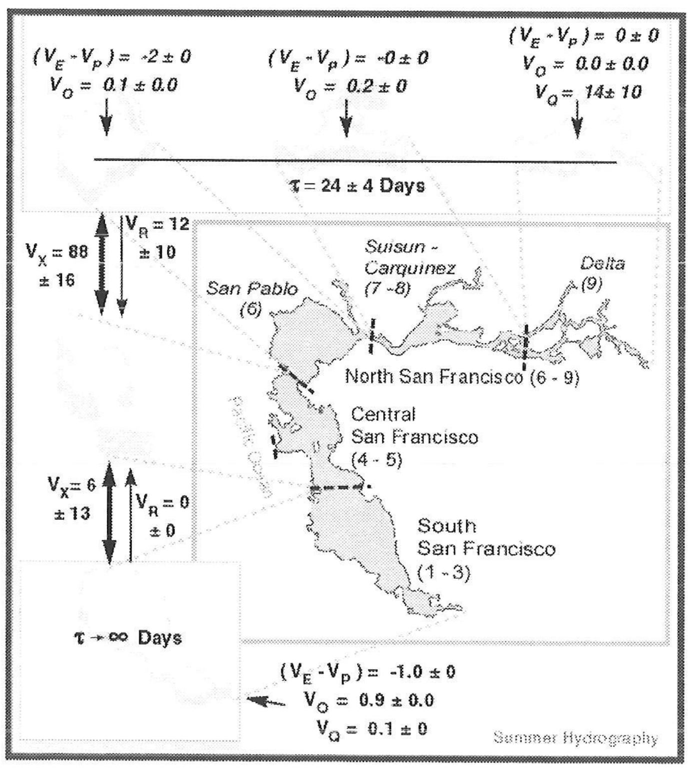

Figure 7 Summer hydrographic fluxes (10^6 m^3 d^{-1}) in San Francisco Bay

Table 6 Estimated inorganic nutrient composition of bay sectors and inflows [a]

Period [b]	*South SF Bay*	*Central SF Bay*	*San Pablo Bay*	*Suisun Bay - Carquinez Straits*	*Delta*	*Sewage*	*Runoff*
			DIP (mmol/m^3)				
w-90	8.0	4.2	2.2	2.7	3.1	130	3.1
w-91	9.9	5.0	3.1	3.7	3.8	130	3.4
w-92	8.5	3.3	2.7	3.1	3.0	130	2.8
w-93	6.0	2.0	2.0	2.0	2.2	130	1.5
w-94	7.6	3.4	2.6	2.7	2.7	130	2.2
w-95	3.9	1.6	1.6	1.4	1.5	130	1.0
s-90			3.2	4.8	4.5	130	3.2
s-91	9.9	4.2	2.7	4.4	4.1	130	3.4
s-92	18.7	4.6	4.1	4.8	4.7	130	3.3
s-93	14.3	3.7	3.1	2.7	2.6	130	1.6
s-94	11.8	5.2	3.6	4.0	3.7	130	2.3
s-95	10.8	3.2	2.0	1.8	1.3	130	1.4
			DIN (mmol/m^3)				
w-90	28	32	27	39	44	1,300	32
w-91	63	38	35	58	53	1,300	54
w-92	41	22	24	48	47	1,300	39
w-93	37	17	25	35	36	1,300	25
w-94	42	26	31	45	43	1,300	38
w-95	39	19	24	20	22	1,300	19
s-90			17	33	30	1,300	27
s-91	24	21	19	37	34	1,300	31
s-92	54	21	21	34	33	1,300	28
s-93	51	25	27	27	25	1,300	19
s-94	54	30	28	34	28	1,300	22
s-95	51	21	14	18	14	1,300	22

[a] Note that sewage composition is assumed to be constant, based on weighted averages for five major treatment plants. Runoff composition listed is for runoff (river flow) into the Delta. There are no data available for most of the South Bay streams, so rounded averages of Delta values are used (2 mmol/m^3 DIP; 30 mmol/m^3 DIN). This should not be critical to the analysis, because sewage is the dominant nutrient input to the South Bay. There are no data for dissolved organic nutrients.

[b] w = winter, s = summer. Shaded winter periods (1993, 1995) are wet years.

Table 7 Estimated inorganic phosphorus loading (10^3 mol/d) into San Francisco Bay

			North San Francisco Bay					
	South San Francisco Bay		San Pablo Bay		Suisun Bay - Carquinez Straits		Delta	
Period [a]	River	Sewage	River	Sewage	River	Sewage	River	Sewage
w-90	1	117	0	13	0	26	43	0
w-91	1	117	0	13	0	26	99	0
w-92	2	117	0	13	0	26	109	0
w-93	4	117	0	13	0	26	200	0
w-94	1	117	0	13	0	26	70	0
w-95	9	117	0	13	0	26	297	0
s-90	0	117	0	13	0	26	26	0
s-91	0	117	0	13	0	26	27	0
s-92	0	117	0	13	0	26	30	0
s-93	0	117	0	13	0	26	26	0
s-94	0	117	0	13	0	26	23	0
s-95	0	117	0	13	0	26	48	0

[a] w = winter, s = summer. Shaded winter periods (1993, 1995) are wet years.

Table 8 Estimated inorganic nitrogen loading (10^3 mol/d) into San Francisco Bay

			North San Francisco Bay					
	South San Francisco Bay		San Pablo Bay		Suisun Bay - Carquinez Straits		Delta	
Period [a]	River	Sewage	River	Sewage	River	Sewage	River	Sewage
w-90	9	1170	0	130	0	260	438	0
w-91	21	1170	0	130	0	260	1566	0
w-92	24	1170	0	130	0	260	1521	0
w-93	63	1170	0	130	0	260	3333	0
w-94	12	1170	0	130	0	260	1216	0
w-95	141	1170	0	130	0	260	5643	0
s-90	3	1170	0	130	0	260	224	0
s-91	3	1170	0	130	0	260	257	0
s-92	3	1170	0	130	0	260	244	0
s-93	3	1170	0	130	0	260	310	0
s-94	3	1170	0	130	0	260	220	0
s-95	3	1170	0	130	0	260	755	0

[a] w = winter, s = summer. Shaded winter periods (1993, 1995) are wet years.

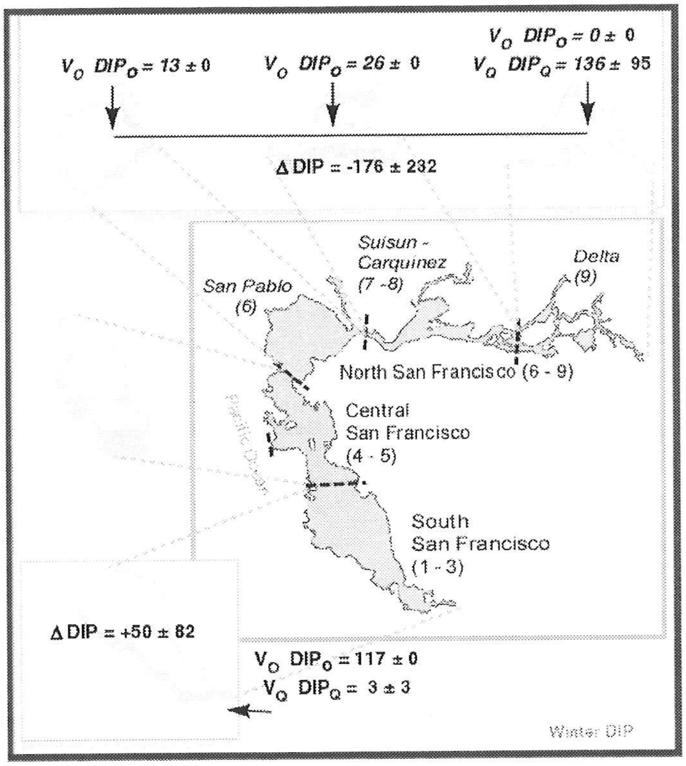

Figure 8 Winter DIP loadings and nonconservative DIP fluxes (10^3 mol d^{-1}) in San Francisco Bay

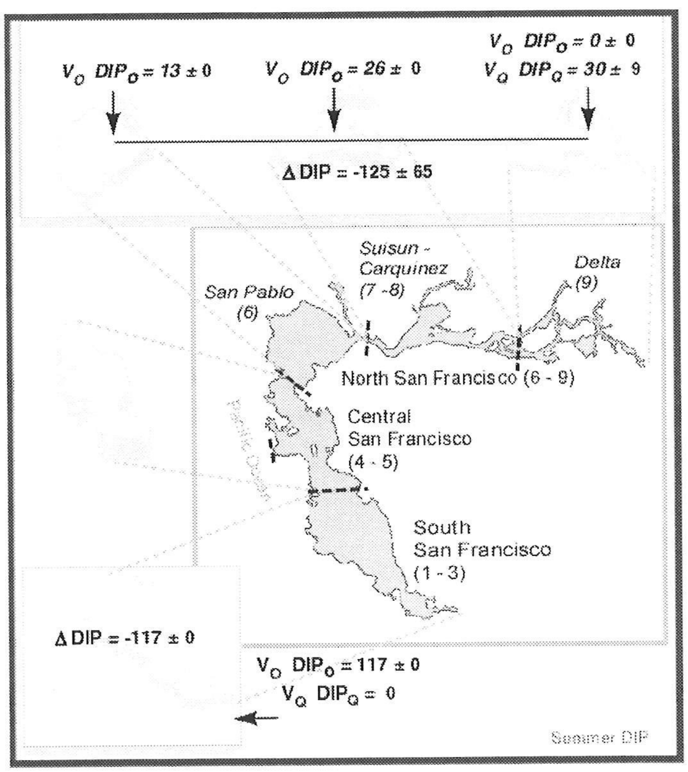

Figure 9 Summer DIP loadings and nonconservative DIP fluxes (10^3 mol d^{-1}) in San Francisco Bay

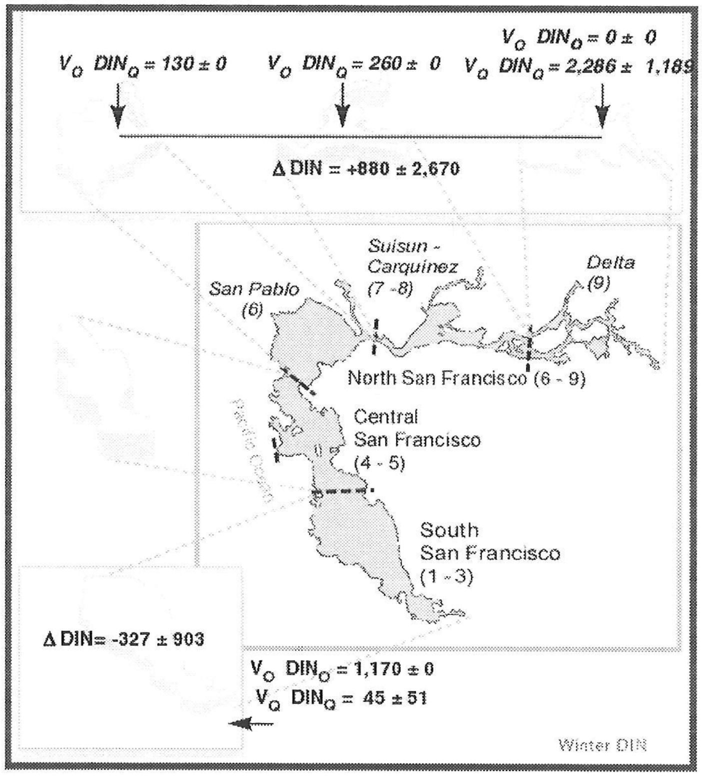

Figure 10 Winter DIN loadings and nonconservative DIN fluxes (10^3 mol d^{-1}) in San Francisco Bay

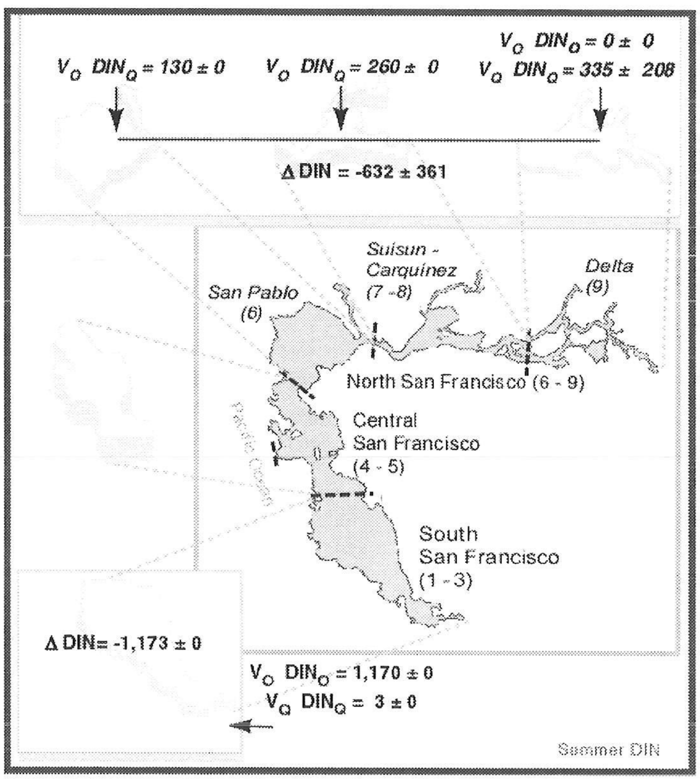

Figure 11 Summer DIN loadings and nonconservative DIN fluxes (10^3 mol d^{-1}) in San Francisco Bay

Table 9 Estimated non-conservative nutrient fluxes (10^3 mol/d) for North and South San Francisco Bay [a]

	DIP				*DIN*			
Period [b]	*budget*	*mean*	*s.d.*	*median*	*budget*	*mean*	*s.d.*	*median*
North San Francisco Bay								
w-90	-443	-466	408	-442	-1,405	-1,511	14,145	-1,103
w-91	-347	-369	1,712	-356	-1,389	-1,087	19,708	-1,103
w-92	-152	-157	328	-148	*-584	-79	81,141	358
w-93	*45	137	869	139	5,550	5,615	20,963	6,061
w-94	-304	-291	558	-275	1,091	1,272	21,430	869
w-95	144	-120	3,363	88	2,018	1,918	12,521	2,123
s-90	---	---	---	---	---	---	---	---
s-91	-169	-167	4,131	-131	-693	-689	9,064	-690
s-92	-82	-82	893	-77	-487	-487	21,254	-432
s-93	-56	-51	191	-46	-200	-161	7,083	-238
s-94	-215	-209	288	-195	-594	-665	12,005	-635
s-95	-104	-103	97	-95	-1,187	-1,304	1,138	-1,378
South San Francisco Bay								
w-90	*-2	26	113	0	-1,265	-1,195	764	-1,121
w-91	142	126	156	89	*160	247	1,199	6
w-92	*2	-6	46	0	-732	-750	405	-748
w-93	-13	-14	50	-14	-672	-722	454	-664
w-94	*1	20	65	13	-716	-659	494	-645
w-95	167	779	6,299	152	1,263	1,087	4,401	1,093
s-90	---	---	---	---	---	---	---	---
s-91	-117	-143	2,208	-111	-1,173	-1,161	661	-1,146
s-92	-117	-84	148	-107	-1,173	-1,079	469	-1,048
s-93	-117	-122	136	-118	-1,173	-1,229	552	-1,149
s-94	-117	110	2,575	-116	-1,173	-1,263	2,590	-1,078
s-95	-117	-121	46	-123	-1,173	-1,216	370	-1,236

[a] Values shown are the budget estimates, the mean, standard deviation, and median of 100 Monte Carlo analyses. Budgeted flux values marked with an asterisk (*) are not statistically significant according to the criterion given in the text.

[b] w = winter, s = summer. Shaded winter periods (1993, 1995) are wet years.

In general, DIP appears to be taken up in North San Francisco Bay in both winter and summer and in South San Francisco Bay during the summer. During the winter, the South Bay usually shows slight DIP release. The conclusion about summer uptake for both North and South Bay seems robust, although somewhat less so for the North Bay based on both the interannual standard deviations and the standard deviations generated for individual years from the Monte Carlo analysis. Closer inspection of the winter data indicates that the winter uptake in the North Bay needs to be interpreted somewhat cautiously. Both the standard deviations generated by the Monte Carlo analysis and the interannual standard deviations are large. In general, however, the four dry winters (the years with somewhat longer exchange times) all exhibit uptake. The wet years show apparent release, but the release rates are low relative to the loading so that small errors in the loading estimates could bias the analyses. Nevertheless, overall the bay appears to be a DIP sink. This conclusion is most robust during the summer and most open to question during the high-runoff winters in the North Bay.

If data for the individual years are examined, DIN was apparently taken up during the first three winters and every summer in North Bay and is generally taken up in South Bay. During the winters of 1993–1995, North Bay appeared to release DIN. These results have to be interpreted very cautiously. In all cases for North Bay, the standard deviations generated by the Monte Carlo analysis are large relative to the estimates of the non-conservative flux. Because the standard deviations are large, we are forced to conclude that the non-conservative DIN flux is not significantly different from 0 (in other words, DIN behaves conservatively) in North Bay. The same conclusion is drawn for South Bay during the winters, but the system is clearly a net DIN sink during the summers.

Discussion

Water Exchange

As is true in many estuarine systems, water exchange in San Francisco Bay is strongly influenced by runoff. While the water and salt budgets do not demonstrate the mechanism of enhanced circulation associated with freshwater inflow, it is undoubtedly related to the establishment of estuarine circulation and enhanced entrainment of more saline deep water into the exit flow of the river water. The importance of this enhanced flow is emphasized by two features of the water and salt budgets.

First, water exchange during the winter in the North Bay was substantially more rapid during the two wet years than during the four dry years. It does not appear that the relationship is a simple proportionality, however, because water exchange was more rapid during the lower flow wet year (1993) than the higher flow wet year (1995). There are at least two possible explanations for this observation. It could be an artifact reflecting the insufficiency of the data to resolve vertical stratification of flow and salinity in the system. Alternatively, extremely high river flow may actually reduce vertical mixing through enhanced stratification and result in a differential discharge of surface water out of the system. That is, the assumption of complete vertical mixing being used in the box model is violated during extremely high flows.

A second feature of water exchange as a function of freshwater inflow is seen in the South Bay. In the absence of significant freshwater inflow during the summer, water exchange is effectively 0.

The paper by Walters and others (1985) is useful for comparison with the exchange times calculated here. These authors concluded that the North Bay has an exchange time (in their paper, the sum of all processes) of days during high flow periods (winter) and months for low flows (summer). These values are consistent with our estimates (see Figures 6 and 7 and Table 5). Walters and others (1985) also experienced problems making summer calculations for the South Bay. After some discussion, they conclude that the exchange time is perhaps as long as ten weeks, although they did not settle on a particular value. For the winter period, they were also equivocal, but suggested that the exchange times could range between three days at the northern end to perhaps two weeks. Qualitatively, at least, these results are consistent with the calculations made here.

Stoichiometric Interpretation of Non-conservative Fluxes

Table 9 summarizes the non-conservative fluxes expressed as daily rates per area and also presents the stoichiometric implications drawn from them. Various features emerge. The winter rates of DIP flux in the North Bay are high relative to summer rates and are also high relative to both summer and winter rates in the South Bay. Moreover, when equation (8) is used to calculate inferred rates of net ecosystem metabolism $(p–r)$, the rates are generally unreasonably high. If we assume a primary production rate of approximately 0.5 g C m^{-2} d^{-1} (Cloern and others 1985), this would be equivalent to about 40 mmol C m^{-2} d^{-1}. Yet the observed rates of ΔDIP converted to estimates of $(p–r)$ are typically of this same magnitude, which implies that $r = 0$. It is unreasonable to expect that none of the primary production is respired. We suspect that much of the DIP uptake in this system is abiotic. Due to the high turbidity of northern San Francisco Bay in particular, this uptake is probably the result of P sorption onto particles (Froelich 1988). DIP was released in the North Bay during the two wet years, again, potentially an abiotic sediment reaction. This conclusion about abiotic uptake may also be consistent with the general pattern of DIP flux.

Table 10 Rates of nonconservative flux normalized per unit area of bay floor and stoichiometric estimates of apparent (*p-r*) and (*nfix-denit*) [a]

Period [b]	*ΔDIP* *mmol* m^{-2} d^{-1}	*ΔDIN* *mmol* m^{-2} d^{-1}	*(p–r)* *mmol* m^{-2} d^{-1}	*(nfix–denit)* *mmol* m^{-2} d^{-1}
North San Francisco Bay (490 km^2)				
w-90	-0.91	-2.9	+96	+12
w-91	-0.71	-2.8	+75	+9
w-92	-0.31	-1.2	+33	+4
w-93	+0.09	+11.3	-10	+10
w-94	-0.62	+2.2	+66	+12
w-95	+0.29	+4.2	-31	-0
s-90	---	---	---	---
s-91	-0.35	-1.4	+37	+4
s-92	-0.17	-1.0	+18	+2
s-93	-0.11	-0.4	+12	+1
s-94	-0.44	-1.2	+46	+6
s-95	-0.21	-2.4	+22	+1
South San Francisco Bay (260 km^2)				
w-90	-0.01	-4.9	+1	-5
w-91	+0.55	0.6	-58	-8
w-92	+0.01	-2.8	-1	-3
w-93	-0.05	-2.6	+5	-2
w-94	+0.00	-2.8	+0	-3
w-95	+0.64	+4.9	-68	-5
s-90	---	---	---	---
s-91	-0.45	-4.5	+48	+3
s-92	-0.45	-4.5	+48	+3
s-93	-0.45	-4.5	+48	+3
s-94	-0.45	-4.5	+48	+3
s-95	-0.45	-4.5	+48	+3

[a] See the text discussion on these estimated process rates.

[b] w = winter, s = summer. Shaded winter periods (1993, 1995) are wet years.

When the estimates of ΔDIP and ΔDIN are converted to estimates of net nitrogen fixation minus denitrification (*nfix–denit*) (equation [9]), the system appears generally to be fixing nitrogen. We were initially perplexed by these observations because they implied that net autotrophic production in San Francisco Bay was so high that nitrogen fixation was required to keep up with the nitrogen demand created by organic production. An estuary receiving high nitrogen loads, where DIN is rarely depleted to phytoplankton growth-limiting concentrations (Hager and Schemel 1996), would not be expected to be a net nitrogen fixing system. This conclusion would remain qualitatively the same regardless of the large uncertainty in the non-conservative DIN flux. To resolve this dilemma, we tentatively concluded that there were likely to be additional nitrogen sources that were not being counted in the budget.

Candidates for these sources included dissolved organic nitrogen (DON), which could decompose to liberate N but not P, atmospheric deposition, or nonpoint source inputs. We cannot evaluate DON loads because of a lack of data. First-order calculations reveal that the required atmospheric input is simply too high to be plausible. There are some model calculations of nonpoint source inputs around the periphery of the bay (Anonymous 1992). Again, these inputs are insufficient. Further analysis of the data suggest that the problem lies with inferring that the ΔDIP is primarily biotically driven in this system. If we assume, for the sake of argument, that the biotic component of ΔDIP is near 0, then ΔDIN would reflect (*nfix–denit*). That is, if DIP and, by extension, DIN is not being taken up to support net autotrophic production, the ΔDIP term in equation (9) goes to 0 and all DIN loss would then be attributable to denitrification. It is unlikely that there is no biological uptake of DIP or DIN in the North Bay.

Peterson and others (1985) used salinity-composition plots of North Bay nutrient data collected during the 1970s to describe nutrient dynamics in this reach. Their results are qualitatively the same as ours, suggesting that the nutrient dynamics of San Francisco Bay have not changed substantially between their 1970s period of record and the 1990s period we analyzed. While they did not attempt to model their data or use it to calculate net fluxes, the shape of the curves they obtained indicate net uptake of nutrients, especially silicate (Figure 6 in Peterson and others 1985), during the summer. This pattern was most pronounced during drier years. Peterson and others (1985) interpreted the non-conservative behavior of silicate as an indication of benthic diatom primary production in northern San Francisco Bay, an entirely credible hypothesis given the high benthic chlorophyll concentrations observed in shallow areas of San Pablo and Suisun bays (Thompson, personal communication, see “Notes”). Thus the non-conservative fluxes of DIN and DIP we observed are likely the result of a combination of abiotic processes (P adsorption), primary production, and heterotrophy (denitrification).

Why don't the stoichiometric equations appear to work very well in San Francisco Bay? While there are other systems in which stoichiometric calculations do not work well, the northern San Francisco Bay case seems unusually bad. We suspect that the answer lies with the extremely high nutrient concentrations in the water column (see Table 6), probably coupled with high turbidity. Particularly for phosphorus, which is known to be particle-reactive (Froelich 1988), these conditions probably result in significant rates of P sorption to sediments.

Possible Consequences of Altered Levels of Waste Treatment

It is useful to examine the budgets that have been presented here and consider what management-related lessons can be learned. Taken as a whole, the nutrient loading into San Francisco Bay is presently dominated by sewage. During the winter, about half the inorganic nutrient loading to this system is sewage; in the summer, the sewage contribution to total loading is about 80%. The spatial distribution of this loading (mostly river in North Bay; mostly sewage in South Bay) has already been discussed. There is some uncertainty as to the origin of the nutrients in the "river nutrient" signal entering the North Bay through the Delta. These nutrients are assumed to originate primarily from agricultural activities in the Delta and the Central Valley, yet the urban areas of Sacramento, Davis, Modesto, and Stockton on the periphery of the Delta (see Figure 2) may contribute significantly to this input via sewage. Regardless of the sources, the resultant nutrient concentrations in San Francisco Bay (see Table 6) are very high relative to most seawater.

Since sewage is such an important nutrient source, it is instructive to ask what has been the effect of wastewater treatment on nutrient loadings to San Francisco Bay? Unpublished data assembled by the California Regional Water Quality Control Board between 1955 and 1985 indicate that daily per capita BOD production by communities discharging waste into San Francisco Bay was about 120 g/person. It should be clarified that this is production, not discharge, of BOD. Between 1955 and 1985, it was estimated that the BOD removal efficiency of STPs went from 30% to 95%. The estimated per capita BOD production is about 50% higher than standard design criteria reported by Tchobanoglous and Burton (1991), three times the values used for widely used rapid assessment techniques (Economopoulos 1993), and well above the waste load of a variety of published estimates assembled by one of us (SVS). We point out that the San Francisco data seem high to underscore possible uncertainty in these estimates.

Based on this BOD loading estimate (120 g/person/d), typical BOD-to-nutrient ratios in domestic sewage and the nutrient loadings estimated in this report; we conclude that treatment is currently removing 75% to 90% of the nutrient load from the waste stream entering sewage treatment plants. Nutrient loads to the bay and nutrient concentrations in it would be substantially higher in the absence of waste treatment to the present level. However, the low primary production of the bay is not a consequence of nutrient limitation so that further nutrient elevation would probably not increase biotic uptake significantly.

The more significant role of waste treatment in this system may be concerning the form of nutrient present and perhaps the pathways of inorganic nutrient uptake. Typically, approximately half of the nutrient load in raw sewage is inorganic. Besides removing nutrients, treatment undoubtedly elevates the proportion of inorganic nutrient. In clear water with low nutrient levels, this might actually enhance biotic nutrient uptake and primary production. In San Francisco Bay, any increase in nutrient removal probably results from abiotic sorption of phosphorus onto particles and perhaps by elevated loss of nitrogen through denitrification.

Before implementation of current treatment practices, the organic carbon loading from waste is likely to have been of greater significance to the San Francisco Bay foodweb and geochemistry than nutrient loading. Using the waste production estimates cited above and standard conversion factors, organic carbon discharged to the bay in the untreated sewage produced by six million people would total about 60×10^6 mol/day (720×10^6 g C/day). Spread evenly over the bay surface of 1,200 km^2, this is equivalent to about 0.6 g C m^{-2} d^{-1}. We can assume that most of this material is relatively reactive and would support heterotrophic activity (respiration and secondary production, broadly defined to include higher organisms as well as bacteria).

Primary production in San Francisco Bay averages about 0.5 g C m^{-2} d^{-1} (Cloern 1985). Phytoplankton biomass is also reactive and supports heterotrophic activity. The conclusion from this simple calculation is that the magnitude of organic matter supplied by waste loading in the absence of treatment could have exceeded the reactive organic matter supplied by primary production. It therefore seems likely that heterotrophic activity might approximately double if that waste load were currently reaching the bay. It should be noted that this simple geochemical calculation provides no insight as to where, within the food web of the bay, this elevated heterotrophy would be most strongly felt. Spatially, waste discharge data used in budgetary calculations suggest that the major impact would be in the South Bay. The slow exchange times there, particularly during the summer, would clearly exacerbate any effects from such high organic loading.

Summary and Conclusions

One of the most striking conclusions we have reached in this analysis is that nutrient data are surprisingly sparse in San Francisco Bay for the sort of mass balance analyses we have performed. This stems in part from the realization that nutrients are not limiting phytoplankton growth or primary production in the bay (Cole and Cloern 1984; Cloern and others 1985). Thus nutrient data have not been needed to accurately model phytoplankton production.

It would be highly desirable for future mass balance analyses and other geochemical modeling efforts, to have better horizontal, vertical, and temporal resolution of water properties in the bay. Because the system can sometimes be vertically stratified, vertical resolution of properties is important—but was not possible in our analysis. Available data are minimal for defining the nutrient and salinity composition of individual sectors in the North Bay and for resolving weak horizontal gradients in the South Bay. Somewhat more detailed data on composition of freshwater reaching the bay (sewage, river, possibly other sources) would be desirable, but distribution in the bay is the critical weak point in the current data set.

More frequent sampling according to a routine sampling protocol, more sampling stations, and sampling for greater discrimination of the vertical distribution of water properties would all be useful for modeling efforts. This sampling should include at least one station (and preferably more) outside the Golden Gate. It should be further emphasized that an adequate sampling regime needs to include the entire bay. Clearly there is material exchange down concentration gradients between North Bay and Central Bay and between South Bay and Central Bay. The system should be considered an interconnected whole.

Despite constraints imposed by limited data, we have been able to develop water, salt, and inorganic nutrient budgets for San Francisco Bay for wet (winter) and dry (summer) seasons during the years 1990 through 1995. To deal with the lack of data, we subjected all budgets to Monte Carlo analysis to derive some measure of the robustness of the estimates. For the most part, the budget calculations are robust; this conclusion appears to be particularly true for the nutrient budgets that were the primary focus of this analysis.

DIP is, in general, taken up by the system. The rates appear to be too high to be attributed primarily to biotic reactions (net ecosystem production). We attribute the uptake to abiotic particle reactions, most probably sorption of DIP onto sediment particles. DIN may also be taken up (although the high standard deviations on the estimated uptake preclude unequivocal definition of this point). The apparent DIN uptake rates would not appear to be consistent with DIP uptake into organic material. We suspect that most of this uptake is associated with denitrification.

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